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WHAT IS DELAYING THE MANIPULATOR REVOLUTION?

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Despite two decades of work on mechanical manipulators and their associated controls, we do not see wide-spread application of these devices to many of the tasks to which they seem so obviously suited. Somehow, a variety of interacting causes has conspired to prevent them from fulfilling their much talked about potential. In part, this appears to be the result of a research effort that was too small, too fragmented, and too discontinuous in time.

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Despite two decades of work on mechanical manipulators and their associated controls, we do not see wide-spread application of these devices to many of the tasks to which they seem so obviously suited. Somehow a variety of interacting causes has conspired to prevent them from fulfilling their much talked about potential. In part this appears to be the result of a research effort that was too small, too fragmented and too discontinuous in time. In part it can be blamed on an under-estimation of the complexity of the problem and the need for contributions from several fields. Often too, design and control of manipulators was tackled as a problem of applying existing techniques to a new device. It appears that in the process basic research on a fundamentally new problem was neglected. Here I will list some of the areas where there appear to be particular gaps in our knowledge which provide opportunities for future work. No doubt there are others that will only become apparent when some of the fundamental issues are settled.

First, it should be noted that most present-day industrial manipulators have an anthropomorphic geometry which has proven adequate for application in parts transfer and which may be useful for parts re-orientation. It appears, however, that the good aspect ratio of a serial kinematic chain of this type may not be appropriate when assembly operations are being considered. In this case, other design parameters such as rigidity and precision may dictate designs which surround the work-piece with structure and which may exploit the advantages inherent in parallel degrees of freedom.

Curiously too, proposed designs tend to vary little over size ranges of several orders of magnitude, despite dramatic scaling effects. It seems reasonable that a device for assembly of large space structures, where compliance of links and inertia are important, may look different from one designed for micro-surgery, where friction and the strength of available materials are limiting factors.

We now understand in a general way the kinematics, statics and dynamics of manipulators. Because of the tedium of algebraic manipulation, the equations of motion have not been developed for many existing devices. This severely restricts the design of adequate control systems and prevents simulation of these devices. Fortunately, techniques are now being developed which can be analysed using computer systems talented at manipulation of symbolic mathematical expressions.

So far, most control systems for manipulators either utilized analog servoes or digital computer simulation of such systems. Very little attention has been paid to the unique capabilities of the digital computer or its poor performance in simulation of linear time-invariant analog systems. Much work remains to be done in exploration of control strategies specifically suited to digital control. There has been much resistance to this approach because the tools of the more traditional approach no longer apply. At the same time such techniques as logical control using a discrete tesselation of state space have shown great promise.

Everyone is aware of the micro-computer revolution. Most view it in terms of a revolutionary drop in cost of central processors. Note however that the cycle time of processors has been relatively constant for a very long time. That is, rapid progress in this field has not helped with tasks which appear to require more computing steps per unit time than are available from present processors. Parallelism, the apparent panacea, actually does not provide the solution, since most tasks of interest here cannot be partitioned suitably into several similar and nearly independent processes.

There is however another revolution in the digital electronics field with perhaps greater ultimate impact: the memory revolution. Since the quickest way to compute a function is to look up the answer it seems that large memories will permit the rapid calculation of complicated functions which now stretch the capabilities of central processors. Work has to be done, however, to develop techniques which will permit the partition of a calculation into parts which can be handled this way, and those which are better tackled in the more familiar fashion.

Traditionally manipulators have been controlled with analog servoes closed separately around each joint. Such systems have proven adequate for many purposes and certainly are simply to design. At high speeds however, they fail because they cannot deal with the varying effective inertias seen by each actuator, the cross-coupling of torques between joints, and the appearance of Coriolis forces. Attempts have been made recently to develop digital computer control techniques based on simplified dynamic models of the device. This approach has been seriously hampered by the difficulty of developing these models and the complexity of the equations of the inverse system.

Work will have to be done to find ways of performing these calculations in real time, perhaps using some of the notions mentioned earlier, such as the use of large look-up tables. Much more wide-spread application of current "industrial robots" would no doubt be triggered by a speed-up of devices used in parts transfer which could result from such a development. Since the technology for making reliable manipulators in the quantities sold today appears to be stable, this certainly is a more likely cause of wide-spread dissemination than reduction in the cost of manipulators.

In assembly, substantial amounts of time are required for fine motions rather than the gross motions more common in parts transfer. At first sight then, the development of adequate control methods based on dynamic models of the manipulator appears unnecessary. Note, however, that in the traditional control system, the actuator signal is derived from the error. Part of the reason that fine motions have to be done so slowly is that otherwise this error has to become large to provide adequate actuator force. Precise small motions thus also require good understanding of the non-linear, time-varying, multi-degree of freedom device being controlled.

It should be noted too that the kind of control system here proposed uses equations which take into account all the interactions between links. This computation cannot be conveniently partitioned into separate processes for each actuator. It is important then that the digital computer implementation not repeat the error of the traditional analog servo systems with separate, parallel computations for each joint.

In assembly operations, manipulators are used quite differently from the way they are in parts transfer. In transfer, the unconstrained motion of the device suggests that position and velocity control is appropriate. In assembly, however, the external constraints imposed by the parts being mated suggests that different modes of operation are needed, perhaps force and torque control. Past work on force and torque sensors and component insertion has gone a long way to showing the need for more work on a general representation for forms of hybrid control. One way to look at it is to consider the degrees of freedom of the device and the number of constraints imposed on it. Some of these constraints may be in position and some in force. But in each case, the total number of such constraints must equal the number of degrees of freedom of the device. A particular difficulty is the situation where statics and dynamics become intermingled — when the device is moving while maintaining prescribed forces and torques.

Even when we are satisfied that the design and control of manipulators is well in hand, we still have to provide commands for their movements. It is clear that in addition to direct and supervisory control by humans there will be a need for autonomous operation. Past experience indicates that manipulators can be programmed for parts transfer and assembly operations, but that a great deal of effort is involved in doing so. Present research is aimed at the development of computer languages which hopefully will allow fairly concise descriptions of the assembly task.

In this effort a number of serious problems have been uncovered. One of these is the inadequacy of presently practiced techniques for the representation of objects. A representation must be tailored to the computational tasks at hand. Representations for objects used in parts design, for graphic display, or for the generation of tapes for numerically controlled machines are typically not very useful for the planning of assembly operations.

In assembly, one has to solve problems dealing with the spatial intersection of objects, mating of surfaces, suitability of surfaces for grasping and so on. New representations for objects must be explored which make these computations possible in a reasonably efficient manner.

In planning an assembly, an astonishing number of complex reasoning tasks have to be tackled. What order to perform operations; which surface to pick an object up by; which part to hold with the vise; whether two manipulators have to be used; where to place a part temporarily not needed; how to use jigs and temporary fasteners and so on. While these problems appear to fall in the dominion of research in machine intelligence, there has been relatively little work in this area of spatial reasoning. Most effort in the past has been concentrated on more sequential, verbal-like reasoning, as evidenced for example in theorem-proving.

While humans find it very easy to answer, at least in an approximate way, questions about space, mechanical linkages and the motion of parts, present computer based techniques are entirely inadequate. Even determining whether two objects intersect may take an inordinate amount of computer time if the representation for the objects and for space are not appropriate. Part of the problem is in fact that we are so good at performing this kind of reasoning, and so unable to introspect about how we do it, that we underestimate how much effort will be required to develop adequate computer programs to simulate these activities.

Most of the past work related to manipulator control has been mission oriented and aimed at near future application. We are now facing the limitations of this approach because there is no adequate base of fundamental research results to build on. One can identify the issues which need immediate attention never-the-less, and I have attempted to describe those I can see. There is much to be done.

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